Design and Analysis of Filtenna using Substrate Integrated Waveguide Cavity

Dissertation submitted to
Visvesvaraya National Institute of Technology, Nagpur
in partial fulfillment of the requirements for the award of the degree

Master of Technology
in
Communication System Engineering

Submitted by

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MT23CMN005

Under the guidance of

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Visvesvaraya National Institute of Technology

Nagpur 440 010 (India)

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Department of Electronics and Communication Engineering
Visvesvaraya National Institute of Technology Nagpur

DECLARATION

I, **Satish A. Sahare**, hereby declare that this dissertation titled **"Design and Analysis of Filtenna using Substrate Integrated Waveguide Cavity"** is carried out by me in the Department of Electronics and Communication Engineering of Visvesvaraya National Institute of Technology, Nagpur. The above thesis work or any part of this work has not been submitted anywhere for the award of any degree or diploma.

Satish A. Sahare (MT23CMN005)
Date:

CERTIFICATE

This to certify that the dissertation titled **"Design and Analysis of Filtenna using Substrate Integrated Waveguide Cavity"** is submitted by Satish A. Sahare in partial fulfillment of the requirements for the award of the degree of Master of Technology in Communication Systems Engineering, VNIT Nagpur. The work is comprehensive, complete and fit for final evaluation.

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Assistant Professor
VNIT, Nagpur

Dr. Ashwin Kothari
Professor & HoD
VNIT, Nagpur

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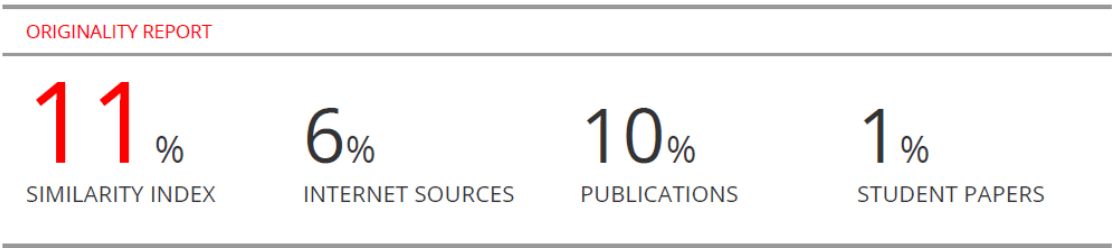


Figure 1: Similarity report

SATISH A. SAHARE
(MT23CMN005)

DATE:

ACKNOWLEDGMENT

I would like to express my deepest gratitude to my esteemed Supervisor, **Dr. Arvind Kumar**, Assistant Professor in the Department of Electronics & Communication Engineering at VNIT Nagpur. His steadfast guidance, exceptional support, and continuous encouragement have been foundational to my journey through this thesis. His expertise, patience, and insightful feedback have been crucial in shaping the direction of this work.

I am grateful to **Dr. Ashwin Kothari**, Head of the Department of Electronics & Communication Engineering at Visvesvaraya National Institute of Technology, Nagpur, for his motivational support throughout this endeavor.

I owe a great deal of gratitude to my family and friends for their unwavering encouragement and understanding during this challenging yet rewarding academic journey.

Finally, my heartfelt appreciation goes to all the individuals who have contributed directly or indirectly to this thesis. Their assistance and cooperation have been invaluable and have greatly contributed to the collaborative spirit that characterizes this work.

6 June 2025 ***Satish A. Sahare***

ABSTRACT

In this research, Patch Filtenna with a High Selectivity and Wide Stop Band Suppression based on Multi-Functional slots enhanced with the Substrate Integrated Waveguide (SIW) cavity and loaded with the ring structure slot on ground plan are presented. The Filtenna employs a modified patch configuration with a simple designed structure having square patch with two- inverted C-Shaped Separated by H-shaped printed on top of patch and ring slot printed on ground plane. Above three slots generated the three resonances with out of band three controllable Radiation Nulls (RNs) to enhance the stop-band suppressed level is generated. An Filtenna prototype with a dimension of 0.78 λ_g× 0.78 λ_g × 0.0316 λ_g. A third-order Patch Filtering Antenna has been designed and simulated, operating frequency from 4.08 to 4.44 GHz with a Fractional Bandwidth of 8.7%. The Antenna achieves Three independently controlled Radiation Nulls at 3.6 GHz, 5.2 GHz and 5.5, contributing to improved selectivity and out-of-band rejection. Furthermore, it exhibits excellent out-of-band suppression with a stopband attenuation.

Keywords: Substrate Integrated Waveguide (SIW) Cavity, Filtering Antenna, Radiation Nulls

CONTENTS

Title Page	**Page No.**
Declaration	ii
Plagiarism Certificate	iii
Acknowledgment	iv
Abstract	v
Contents	vi
List of Tables	viii
List of Figures	ix
List of Abbreviations	xi
CHAPTER I INTRODUCTION	1
1.1 Overview of Filtenna	2
1.1.1 Antenna	2
1.1.2 Filter	2
1.1.3 Integration of Antenna and Filter	3
1.2 Basic Of Filtenna	3
1.3 Filtering Antenna Design Methods	4
1.3.1 Cascaded Filters and Antennas	4
1.3.2 Coupled-Resonator Filter Concept	4
1.3.3 Microstrip Antennas with built-in Filtering capabilities	6
1.4 Design Geometry and Overview	7
CHAPTER II LITERATURE REVIEW	8
2.1 Literature Survey	9
2.2 Motivation	13
2.3 Problem Statement & Objectives	14
2.3.1 Problem Statement	14
2.3.2 Objectives	14
2.4 Hardware and Software tools	14

CHAPTER III FILTENNA DESIGN FRAMEWORK & STEPS 15
3.1 Framework of Filtenna Design 16
3.2 Filtenna Design Configuration 18
3.3 Antenna Design Process 18
3.3.1 Antenna 1 20
3.3.2 Antenna 2 21
3.3.3 Antenna 3 23
3.4 Working Mechanism 25

CHAPTER IV PROPOSED THIRD ORDER FILTENNA DESIGN 28
4.1 Introduction 29
4.2 Proposed Third Order Filtenna Design 29
4.3 Design Parameter 30
4.4 Filtena Design Process and Evolution 31
4.5 Working Mechanism 35

CHAPTER V RESULTS AND CONCLUSION 39
5.1 Results 40
5.2 Conclusion 42

CHAPTER VI REFERENCES 43
6.1 References 44

LIST OF TABLES

Table No	Description	Page
1	Antenna Structure Parameters	19
2	Filtenna Structure Parameters	31
3	Proposed Filtenna Compare with other Existing Filtenna	41

LIST OF FIGURES

1 Similarity Report iii

Figure No.	Description	Page No.
1	(a) Block diagram of a cascaded filter-antenna configuration, and (b) its corresponding spectral response. I/O: input/output.	4
2	(a) Equivalent circuit of a second-order in-series co-designed filtering antenna, and (b) Corresponding S-parameter response.	5
3	(a) Parallel co-designed filtering antenna and (b) Comparison of gain responses between a traditional antenna and a parallel-configured co-designed filtering antenna	6
4	(a) Patch Designed Second Order Antenna without Filtering Response, (b) Ground Plane with Ring Slot, (c) Radius & Distance of SIW Cavity	18
5	a) Microstrip Feed with SIW Cavity and (b) Simulated S-Parameter (c) Realized Gain	20
6	(a) Antenna 2, 2-inverted C-shaped separated by Horizontal slot, (b) Simulated S-Parameter, (c) Realized Gain	22
7	(a) Antenna 2, 2-inverted C-shaped separated by Horizontal slot, (b) Ring Slot on Ground	23
8	Dual Resonance Antenna (a) Simulated S-Parameter (b) Realized Gain	24
9	Distributions of Current on the Antenna Structure at (a) f_1= 4.73 GHz (b) f_1 = 4.87 GHz (c) f_{n1} = 3.3 GHz (d) f_{n2} = 6.3 GHz.	26
10	Proposed Simulated Third Order Filtenna, (a) Patch (b) Ground Plane (c) Radius & Distance of SIW Cavity	30
11	Proposed Filtenna Evolution and Comparison	31

Figure No.	Description	Page No.
12	S-Parameter Comparison of Simulated Antenna Designs	32
13	Realized Gain Comparison of Simulated Antenna Designs	33
14	Surface Current Distribution at (a) f1 = 4.08 GHz, b) f2 = 4.29 GHz and (c) f3 = 4.438 GHz	34
15	Electric Field Distribution at (a) f1 = 4.08 GHz, (b) f2 = 4.29 GHz and (c) f3 = 4.438 GHz	34
16	1D view of Radiation Patterns at (a) 4.08, (b) 4.29, and (c) 4.438 GHz.	38
17	3D view of Radiation Patterns at (a) 4.08, (b) 4.29, and (c) 4.438 GHz.	40

LIST OF ABBREVIATIONS

SIW	Substrate Integrated Waveguide
1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional
TE	Transverse Electric
TM	Transverse Magnetic
CSTMWS	Computer Simulation Technology Microwave Studio
EM	Electromagnetic
RN	Radiation Null

CHAPTER I

INTRODUCTION

1.1 Overview of Antenna and Filter

Antennas & filters have traditionally been separate parts of communication systems. Filters are used to separate desired frequency range and reduce undesired signals or noise, while antennas act as transducers, converting electrical impulses into electromagnetic fields and vice versa. However, the requirement for high-performance, multipurpose devices and the ongoing drive toward system downsizing have sparked the creation of integrated components [1].

1.1.1 Antenna

An essential part of wireless communication systems, antennas allow electromagnetic waves to be transmitted and received. It acts as a bridge connecting electrical circuits and wave propagation in free space. When operating in transmitting mode, the antenna transforms electrical power from a transmitter into airborne electromagnetic radiation. It detects incoming electro-magnetic impulses and converts them back into electrical data for processing while in receiving mode. The size, shape, and structure of antennas vary greatly according on the application and frequency range they are designed for Horn, dipole, and microstrip (patch) antennas are often used varieties [2]. Antenna performance is influenced by a number of critical characteristics, including gain, bandwidth, radiative pattern, and directivity.

1.1.2 Band-Pass Filter

A band-pass filter is a frequency-selective network that allows signals within a defined frequency band to pass through while blocking signals outside this band. It is defined by two cutoff frequencies lower and an upper limit. Signals that fall outside this range are attenuated significantly, minimizing unwanted noise or interference.

By separating the required signal spectrum from extraneous frequencies, these filters are essential to communication systems. This selective frequency control is important in both transmitting and receiving circuits, helping to improve overall system performance and reduce interference from other signals [3].

1.1.3 Integration of Antenna and Band-Pass Filter

In practical communication setups, an antenna is often integrated with a band-pass filter to enhance signal quality. On the transmitting side, the band-pass filter ensures that only signals within the intended frequency band are radiated by the antenna, reducing out-of-band emissions [4]. On the receiving side, it helps suppress unwanted frequencies before the signal is processed, improving signal-to-noise ratio and preventing interference. But this type of Integration can increase the system size, Degraded performance, and also increases the manufacturing costs.

1.2 Basic of Filtenna

Many technologies have come together in the constantly changing field of wireless communication as a result of the search for small, effective, and multipurpose components. The incorporation of filtering functions into antenna structures, also known as filtering antenna or Filtennas, is one such convergence that has attracted a lot of attention lately. These innovative devices combine the conventional functions of filter and antenna into one unit, simplifying the RF front-end design[5]. Filtennas are engineered to incorporate filtering functions within their physical structure, thereby enhancing frequency selectivity and effectively mitigating undesired signals or electromagnetic interference also it can reduce system size, enhanced performance, and reduce manufacturing costs. In recent years, a variety of high-performance Filtennas utilizing different transmission media have been progressively developed, including microstrip patch Filtennas[6], substrate integrated waveguide (SIW) Filtennas[7], dielectric resonator-based Filtennas[8], and rectangular waveguide Filtennas[9].

The integration of filtering capabilities into antenna structures has its roots in early studies involving coupled resonator systems and bandpass filtering within the domain of microwave engineering. With advancements in the field, researchers explored the use of resonant configurations and impedance-matching strategies to tailor antenna frequency responses, thereby introducing inherent filtering properties. By exploiting the natural frequency-selective behavior of antenna elements and incorporating principles derived from filter theory, the concept of filtering antennas evolved into an effective and versatile approach for contemporary wireless communication systems.

Selectivity is a crucial performance metric for Filtennas, attracting considerable interest for its role in isolating target signals from adjacent or interfering frequencies. Filtennas with high selectivity are characterized by narrow passbands and steep roll-off responses, making them well-suited for applications requiring precise frequency discrimination. Such that, this type of devices is used in a various application. One widely adopted technique to enhance selectivity involves generating Radiation Nulls (RNs) in close proximity to the Passband[10].

1.3 Filtering Antenna Design Methods

This section presents three representative methods for designing filtering antennas. A comparative analysis of the benefits and limitations of each method is provided.

1.3.1 Cascaded Filters and Antennas

As shown in Fig. 1(a), antennas and the filters are typically coupled in a cascaded manner via a 50-Ω interface. to extract the desired signals and attenuate unwanted out-of-band components. This approach is simple and practical, allowing independent design and tuning of the antenna and filter elements[11].

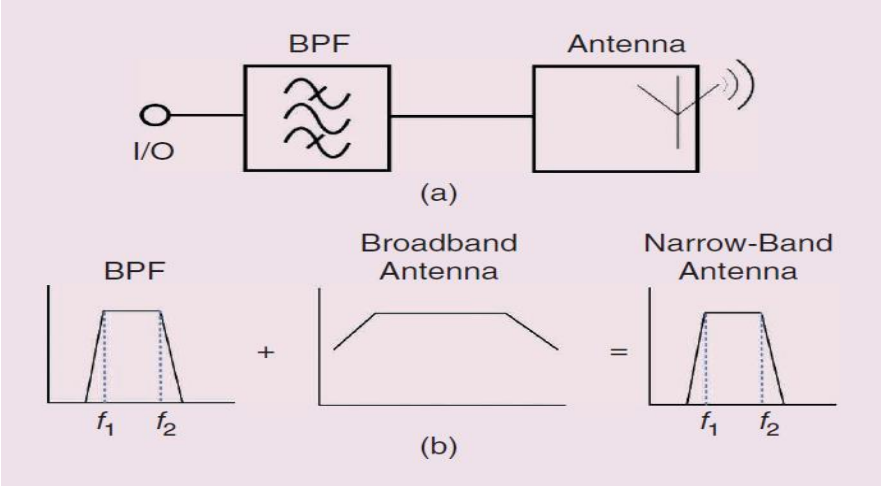


Figure 1. (a) Block diagram of a cascaded filter-antenna configuration, and (b) its corresponding spectral response. I/O: input/output.

To guarantee optimal system performance, a broadband antenna is usually combined with a limited bandwidth bandpass filter (BPF). As illustrated in Fig. 1(b), the BPF predominantly governs the overall frequency response, enabling straightforward reconfigurability by modifying the filter characteristics. This cascaded approach has a number of drawbacks despite its simplicity. It demands a wideband antenna—broader than the BPF's bandwidth—which can be particularly difficult to achieve for high-Q structures such as microstrip patch antennas. Furthermore, the separation between components increases system complexity, size, and the number of interconnections, leading to a bulkier RF front-end. Imperfect matching and transitions between the filter and antenna may also introduce additional insertion loss, especially near the band edges, which can degrade signal integrity.

1.3.2 Coupled-Resonator Filter Concept

To overcome the limitations of traditional cascaded filter-antenna systems, co-design approaches have been introduced for seamless integration. One effective method uses a bandpass filter (BPF) synthesis technique, where the antenna also acts as the final resonator. This approach, illustrated in Fig. 2, can be modeled using a coupling matrix, with the frequency response shown in Fig. 2(b).

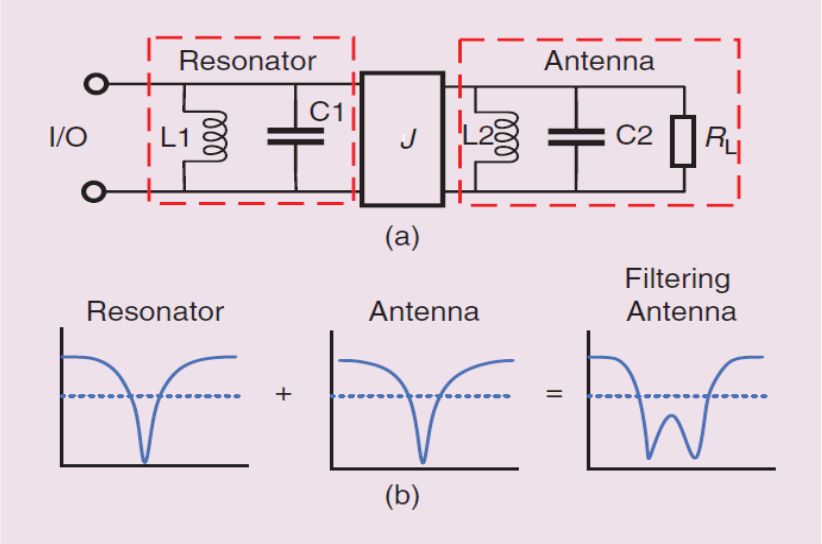


Figure 2. (a) Equivalent circuit of a second-order in-series co-designed filtering antenna, and (b) Corresponding S-parameter response.

While resonant antennas typically suffer from narrow impedance bandwidths, integrating them into the filter structure enables second-order responses with dual resonances, enhancing both bandwidth and selectivity. Compared to the cascaded configuration, this co-designed system reduces size by removing 50Ω interfaces[12], improves efficiency, eases antenna bandwidth constraints, and suppresses higher-order harmonics more effectively. But these designs can introduce complexity and extra losses.

1.3.3 Microstrip Antennas with built-in Filtering capabilities

A recent advancement in filtering antenna design is the combining the function of filter and antenna technique, which eliminates the need for a separate filtering circuit. This technique uses a parallel arrangement, as seen in Fig. 3(a), in which the antenna is combined with resonant components to produce band-stop outputs on both ends of the target passband. As seen in Fig. 3(b), this produces a gain profile that resembles a bandpass. There is little effect of the additional resonators on the antenna's in-band performance because they function outside the passband.

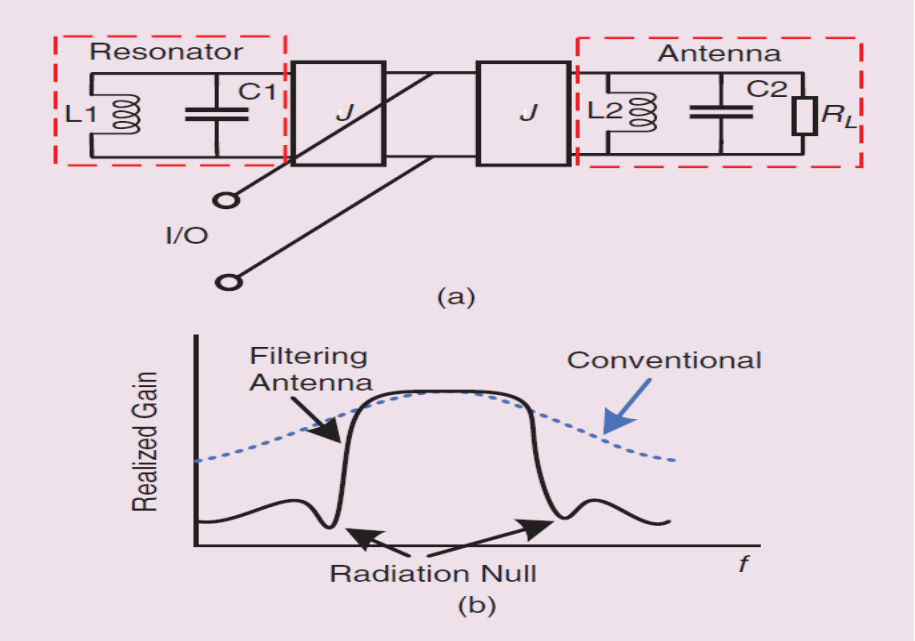


Figure 3. (a) Parallel Co-Designed Filtering Antenna and (b) Comparison of gain responses between a traditional Antenna and a Parallel-Configured Co-Designed Filtering Antenna.

The parallel structure also facilitates the inclusion of cross or source-load couplings, enabling the creation of Radiation Nulls near the band edges. These nulls can be constructed to facilitate band control and frequency selection. A key design challenge lies in effectively generating and positioning these nulls. Notable advantages of the integration technique include increased radiation efficiency and less insertion loss [13]. The most compact approach involves designing microstrip antennas with built-in filtering capabilities. In this method, the radiating element itself is tailored to provide frequency selectivity, reducing the need for external components. Techniques such as slot incorporation, terminal double-branch microstrip lines, multi-arm feed networks, and frequency-selective coupled-line structures are commonly employed to produce Radiation Nulls, thereby enhancing out-of-band signal suppression.

1.4 Design Geometry and Overview

This research work proposes, a high-performance microstrip patch filtering antenna with ring structure on ground plan is designed. that achieves both high selectivity and wide stopband suppression through the use of multi-functional slots and SIW cavity integration. Multi-functional horizontal slot, and two- inverted C slots are embedded into the patch to generated two frequency resonant mode and introduce transmission zeros. To facilitate the generation of an additional resonant mode, an H-shaped slot is integrated into the structure of the driven patch. A substrate integrated waveguide (SIW) cavity is incorporated to guide the waves efficiently and limit out-of-band radiation. Additionally, a ring-shaped slot is etched on the ground plane, which introduces Radiation Nulls near the passband and contributes to stopband extension. To experimentally validate the proposed design, a prototype antenna was fabricated, featuring a compact form factor of 0.78 $\lambda_g \times 0.78\ \lambda_g \times 0.0316\lambda_g$. The realized Filtenna successfully achieves triple-mode impedance matching and maintains stable gain performance over a wide operational bandwidth ranging from 4.08 to 4.438 GHz (corresponding to 8.45% fractional bandwidth).

CHAPTER II

LITERATURE REVIEW

2.1 Literature Survay

[1] Quan Da Liu, Qing Dong, Jun Xiang Wen, Liang Hua Ye, Duo-Long Wu and Xiu Yin Zhang. “Compact Wideband Patch Filtenna with Enhanced Out-of-Band Suppression”. This Paper Proposes, Filtennas are designed using three different methods.

- The first strategy uses an impedance-matching network to cascade the filter and the antenna in a traditional manner. However, this approach adds additional loss and expands the antenna size.
- Designing a unique feed structure with a filtering function is the second technique. Nevertheless, this approach also results in extra insertion loss.
- The third strategy involves designing antennas with filtering functioning characteristics, which efficiently reduces additional loss and minimizes bulk.

A compact and broadband Patch Filtenna with a straightforward design has been introduced with the two layer of same substrate used. where Γ-shaped and inverted Γ-shaped slots are employed to generate extra resonant modes and a low-frequency radiation null. Additionally, a Π-shaped slot is incorporated into the main patch to create a second resonance and a high-frequency radiation null. These modifications effectively expand the impedance bandwidth and enhance stopband attenuation, making the design efficient for integrating filtering capabilities directly into the antenna structure.

[2] Xin Zhou, Gang Zhang, Kam-Weng Tam, Huawei Lin, and Zhuowei Zhang “Highly Selective Filtennas with Wide-Stopband Based on Multifunctional Slots-Loaded Substrate-Integrated Cavity”. This study proposes Enhancing frequency selectivity by introducing Radiation Nulls (RNs) near the passband and Method used in this research.

- A filter is built with stacked dual-slotted substrate-integrated cavities (SICs) as the first way to attain excellent selectivity using multilayered structures.
- Parasitic patch coupling is the second way to attain high selectivity. We show a highly selective filtering slot antenna with a patch built on top of it. The frequency selectivity is enhanced by the use of combined electric & magnetic coupling in stacked patches.
- The third way to attain great selectivity is to add pins or slots to a single-layer filter.

- Compact Filtenna using slot-loaded substrate-integrated cavities, by integrating half mode patch radiators. The half-wavelength resonator's length L alone determines its resonant frequency, which may be written as

$$f_{\text{half-wavelength}} = \frac{c}{2\sqrt{\varepsilon_r}}\frac{1}{L} \quad (1)$$

H-shaped and C-shaped slots, the design achieves wide stopband suppression, improved selectivity, and a simplified structure. The Proposed Filtenna consist of a rectangular SIC should be inserted into the H-shaped slot. To guarantee that the antenna functions at the intended frequency, modify the SIC's width. To ascertain the intended BW and the location of RN, reasonably modify the H-shaped slot's specifications. To locate RNs, appropriately size the feedline and the CPW structure.

[3] Kun-Zhi Hu, Kang-Hong Yuan, Dajiang Li, Ming-Chun Tang, Zhiyuan Chen, and Dong Yan "A Single-Layer Differentially Fed Filtenna with Controllable Radiation Nulls Using Hybrid SIW Cavity and Patches". This paper addresses Two square patches, four matching pins, a SIW cavity, and a handful of complementary split ring resonators (CSRRs) make up the filtenna that is being presented. The SIW cavity, which reverberates at its TE210 mode, is working in tandem with the two patches, which are resonating at their TM10 modes. This allows the antenna to boost its impedance bandwidth & gain values. When operating in its basic TM10 mode, the square patch's dimensions can be computed by

$$L_{patch} \approx 0.32\frac{\lambda_0}{\sqrt{\varepsilon_r}} \quad (2)$$

It offers controllable Radiation Nulls, improved bandwidth, and simple structure, achieving better integration and filtering than previous designs.

[4] Chi Fan, BianWu, Yue-Lin Wang, Han-Yu Xie, and Tao Su "High-Gain SIW Filtering Antenna with Low H-Plane Cross Polarization and Controllable Radiation Nulls". A high-gain SIW filtering patch antenna with low H-plane cross-polarization and tunable Radiation Nulls is proposed.

- The antenna features a radiating patch that is integrated with three pairs of shorting

pins and a single-layer substrate integrated waveguide (SIW) cavity.

- The addition of shorting pins enhances antenna gain and suppresses cross-polarization in the H-plane.
- A central long slot divides the TE_{110}-mode cavity into two half-mode sections and facilitates magnetic coupling between these sections and the radiating patch.
- An additional shorter slot enables both electric and magnetic coupling with the left half-mode cavity, introducing tunable radiation nulls for improved frequency selectivity.
- The frequency positions of the radiation nulls can be adjusted by modifying the short slot's dimensions

To add further inductance, three sets of shorting pins have been inserted into the patch at the correct locations for this study. The shorting pins' inductance value can be found using

$$L_{\text{pins}} = \frac{\mu_0}{2\pi}\left[h \ln\left(\frac{h+\sqrt{h^2+d^2}}{d}\right) - \sqrt{h^2+d^2} + \frac{h}{4} + d\right] \quad (3)$$

These features create adjustable Radiation Nulls that enhance selectivity, with their positions controlled by slot parameters.

[5] Kirti Dhwaj, Joshua M. Kovit, Haozhan Tian, Li Jun Jiang, and Tatsuo Itoh "Half-Mode Cavity-Based Planar Filtering Antenna with Controllable Transmission Zeroes". This paper proposes a two-pole filtering antenna is formed by combining a half-mode SIW cavity with a standard SIW cavity.

- Electric coupling between the cavities is achieved using a coplanar waveguide (CPW).
- Using a radiating microstrip feed, source-load coupling is introduced.
- This arrangement introduces transmission zeros at both edges of the passband, enabling a quasi-elliptic filtering characteristic.
- The TZ locations can be tuned by adjusting the feed line length and terminating it with a coaxial line.
- The design features a compact structure with low cross-polarization, while maintaining high gain and efficient performance.

The transmission-line model's resonance frequency of the HMSIW cavity, f2, can be calculated using the constraint Im{Yin} = 0, where

$$\frac{Im\{Y_{\text{in}}\}}{Y_o} = \frac{B}{Y_0} - \cot(\beta a_2) \quad (4)$$

It achieves a compact, single-layer structure with controllable TZs, low cross-polarization, and stable gain, improving upon previous designs.

[6] Bohai Zhang, Quan Xue "Filtering Antenna with High Selectivity Using Multiple Coupling Paths from Source/Load to Resonators". A high-selectivity filtering antenna is realized using a novel coupling scheme that introduces cross-coupling between the source/load and non-adjacent resonators. The filtering antenna operates through three main steps:

- Two rectangular patches are utilized to replace the final two resonators typically formed by microstrip line resonators.
- In the filter configuration, the radiating elements are positioned so that their radiated quality factor matches the external quality factor found in the final resonator.
- The coupling between the radiating element and its preceding resonator is designed to mirror the coupling between the last two resonators in the reference filter.

This allows up to *N* Radiation Nulls with *N* resonators, enhancing boresight gain selectivity. The design uses a mix of open- and short-ended stubs to simplify implementation.

[7] Kirti Dhwaj, Haozhan Tian, and Tatsuo Itoh "Low-Profile Dual-Band Filtering Antenna Using Common Planar Cavity". This work presents a dual-band filtering antenna with orthogonal polarization in each band, implemented using single-layer substrate integrated waveguide (SIW) technology. A compact configuration is achieved by employing a dual-mode rectangular SIW cavity that simultaneously supports two orthogonal resonant modes. These modes are individually coupled to slot-loaded SIW cavities, enabling radiation in two frequency bands with orthogonal polarizations. Dual Mode rectangular SIW cavity's TMmn0 mode's resonance frequency, fC, can be determined by

$$f_C = f_{mn0} = \frac{c_0}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{b_1}\right)^2 + \left(\frac{n}{a_1}\right)^2} \quad (5)$$

[8] Xinwei Chen, Fengxian Zhao, Liyun Yan, and Wenmei Zhang "A Compact Filtering Antenna with Flat Gain Response Within the Passband". A two-pole Butterworth bandpass filter is initially designed and then transformed into a filtering antenna by replacing the second resonator and output port with a fan-shaped patch antenna integrated with a defected ground structure (DGS). This configuration results in improved performance over conventional antennas, offering a flatter in-band gain response, enhanced selectivity at the passband edges, and a broader operational bandwidth.

2.2 Motivation for Filtenna Design

The primary motivation for designing Filtennas lies in the integration of filtering and radiation functions within a single, compact component to enhance overall system efficiency and simplify architecture. Traditional RF front-end designs utilize separate filters and antennas connected by transmission lines, which can result in increased insertion loss, larger footprint, and performance degradation due to impedance mismatches and additional interconnections. Filtennas overcome these limitations by embedding the bandpass filtering functionality directly into the antenna structure, enabling simultaneous filtering and radiation of signals. This integration facilitates improved frequency selectivity by generating Radiation Nulls near the edges of the passband, effectively suppressing out-of-band interference without requiring extra filtering elements. The desired filtering response is achieved by carefully designing the antenna's resonant modes and coupling mechanisms, providing precise control over bandwidth and frequency response. As a result, Filtennas offer advantages such as lower insertion loss, reduced size, and enhanced spectral purity, which are essential for communication systems operating in crowded spectral environments. This concept underpins continuous developments in Filtenna technology, aimed at supporting applications such as cognitive radio, advanced wireless communication systems, and modern radar Technologies.

2.3 Problem Statement & Objectives

2.3.1 Problem Statement

- Design and Analysis of Filtering Antenna by using SIW Cavity with the ring structure on the ground plan.

2.3.2 Objectives

- Integrate filtering and radiating functions into a single compact device.
- Improve bandwidth control and suppress higher-order harmonics.
- Improve frequency selectivity by introducing Radiation Nulls close to the edges of the passband.
- Achieve strong out-of-band suppression to reduce interference.

2.4 Hardware and Software tools

- CST Microwave Studio Suite
- Vector Network Analyser (VNA)

CHAPTER III

FILTENNA DESIGN FRAMEWORK AND STEPS

3.1 Framework of Filtenna Design

A Filtenna is a compact device that combines the functions of a bandpass filter and an antenna into a single structure. This integration allows the device to selectively allow signals within certain frequency bands while simultaneously radiating them, effectively blocking out unwanted frequencies. The benefits of such integration include a reduced footprint, lower insertion losses, and simplified circuitry, which are crucial for modern wireless systems that demand both high performance and miniaturization[14].

To design an effective Filtenna, one must understand the operating principles of both antenna and filter components. Antennas are designed to radiate efficiently at specific resonant frequencies[15]. The resonant frequency of a typical microstrip or slot-based antenna can be estimated using the relation:

$$f_r = \frac{c}{2L\sqrt{\varepsilon_{eff}}} \tag{6}$$

where:

f_r = the Resonant Frequency,

c = Speed of Light in Vacuum (3×10^8 m/s),

L = Effective Length of the Resonant Structure,

ε_{eff} = Effective Dielectric Constant of the Substrate.

To achieve distinct resonant frequencies, the antenna geometry can be modified to support multiple modes. This can be accomplished by introducing slots, stubs, folded arms, or metamaterial-inspired structures like split-ring resonators (SRRs)[16], which allow the antenna to resonate at additional frequencies due to localized current paths and reactive loading effects.

The filtering function in a Filtenna ensures that only signals within a desired frequency range reach the antenna's radiating aperture. This is controlled by the filter's center frequency (f0), bandwidth (BW), and quality factor (Q). The quality factor for a specific passband has been defined as follows:

$$Q = \frac{f_0}{BW} \tag{7}$$

Sharper selectivity, or the filter's ability to suppress out-of-band signals more successfully, is indicated by a larger Q. In practical designs, filter behaviour is implemented using lumped LC elements, distributed lines, or resonant cavities such as those found in Substrate Integrated Waveguide (SIW) configurations[17]. In a Filtenna, the filtering structure is embedded into the radiating component rather than added as a separate unit. This embedding alters the surface current distribution and electromagnetic behavior such that radiation only occurs at frequencies that pass through the filter. Thus, the structure intrinsically suppresses undesired frequencies without external circuitry.

3.2 Filtenna Design Configuration

The phases of the Filtenna make up this Filtenna design framework. It consists of four step which shows that the design parameter and comparison among them with different structure printed on filtenna. that the Starting with a standard microstrip-fed substrate integrated waveguide (SIW) patch resonator with a vertically oriented slot carved in the opposite direction, antenna 1 forms the first configuration. In the second stage by adding the central horizontal slot distributes two inverted C-shaped slots, which are integrated to create two horizontally slots printed on the patch. The 3rd step of design process, embedding a ring-shaped slot on the metallic ground plane. Because of this, two peaks generated and it shows the antenna behavior but not filtering characteristics. And last 4th step, the ring structure slot and two inverted C-shaped patches are separated by an H-shaped slot that is printed on the ground plane and cut in opposite directions. three peaks generated and it shows the antenna and filtering behavior.

3.3 Antenna Design Process

To facilitate a comprehensive understanding of the design methodology and structural evolution of the Second-Order Antenna without Filtering function, below figures illustrates the step-by-step progression of the antenna development across three distinct stages. Each stage incrementally enhances the antenna's performance by incorporating additional structural elements[18].

The Rogers RT/Duroid 5880 single-layer dielectric substrate, which has a metal backing, is used to implement the full antenna system. This substrate is selected for its excellent high-frequency performance, offering a low relative permittivity of 2.2 and a minimal dielectric loss tangent of 0.001, ensuring minimal signal degradation and high radiation efficiency. The substrate thickness is maintained at 1.5 mm, balancing mechanical stability and electromagnetic performance.

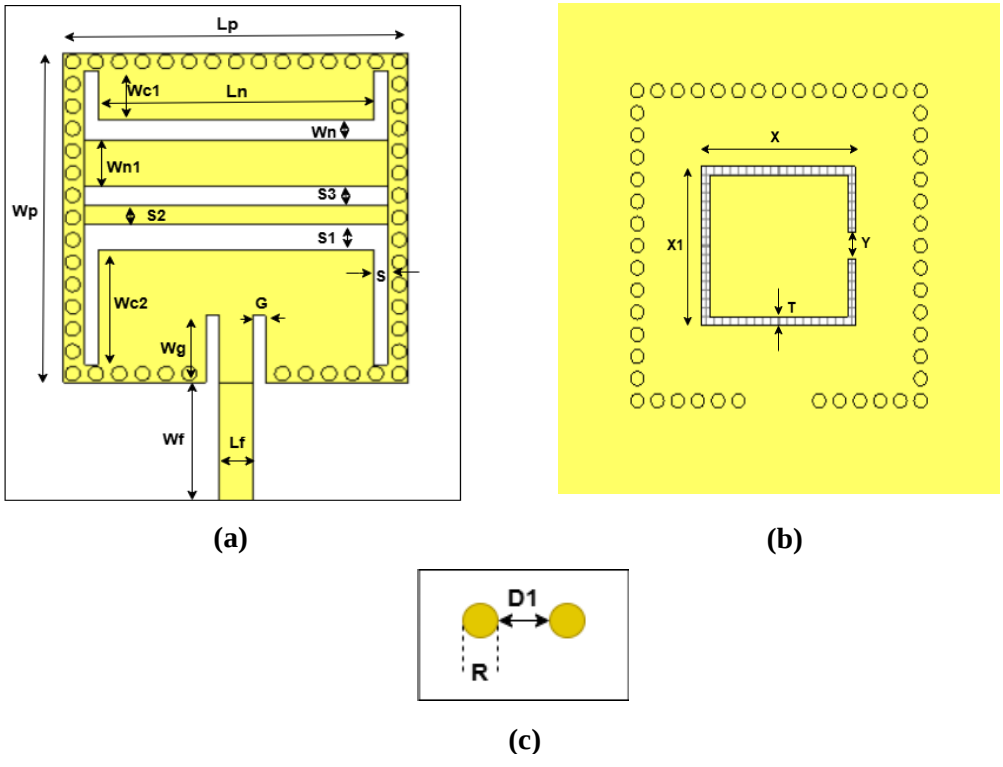


Figure 4. (a) Patch Designed Second Order Antenna without Filtering Response, (b) Ground Plane with Ring Slot, (c) Radius & Distance of SIW Cavity

The Table 1. shows that the design parameters of the Dual Resonance Antenna.

Lp	Wp	Ln	Wc1	Wn	Wn1	S1	S2	S3	Wc2	Wg
37	37	29.5	5.5	2.3	5.2	2.85	2.1	2.15	12.9	7.5

Lf	Wf	G	S	R	D1	X	X1	T	Y
3.6	13.5	1.4	1.5	0.8	0.9	19	18	1	3

Table 1. Antenna Design Parameters (In mm)

Fig. 4 presents the detailed geometry of the two resonance Antenna, which integrates both radiation and compact structure functionalities. The antenna architecture is based on a substrate integrated waveguide (SIW) cavity, which has been strategically modified to support dual-band operation through the incorporation of multiple slot perturbations. Specifically, a horizontal slot and an inverted C-shaped slot are etched on the top patch surface of the SIW cavity, functioning as key elements in tailoring the current distribution and enhancing the resonance behaviour. Complementing these modifications, a ring-shaped conductive structure is patterned on the metallic ground plane to further influence the electromagnetic field distribution and aid in achieving the desired frequency response without filtering function. The antenna is excited using a coplanar waveguide (CPW) feeding configuration, which offers low insertion loss, easy integration with planar circuits, and compatibility with high-frequency operations.

The substrate diamensions is Ls=50 mm and Ws=54 mm the inclusion of the inverted C-shaped slot serves a dual function. it introduces additional resonance paths while simultaneously segmenting the SIW cavity into two coupled half-mode resonators. This configuration leads to a second-order Antenna behavior. below figures illustrates the step-by-step progression of the antenna development across three distinct stages.

3.3.1 Antenna 1

Antenna 1 serves as the initial configuration, comprising a conventional microstrip-fed substrate integrated waveguide (SIW) patch resonator with a vertically oriented slot etched in the opposite direction. This baseline structure establishes the fundamental operating mechanism for the Filtenna.

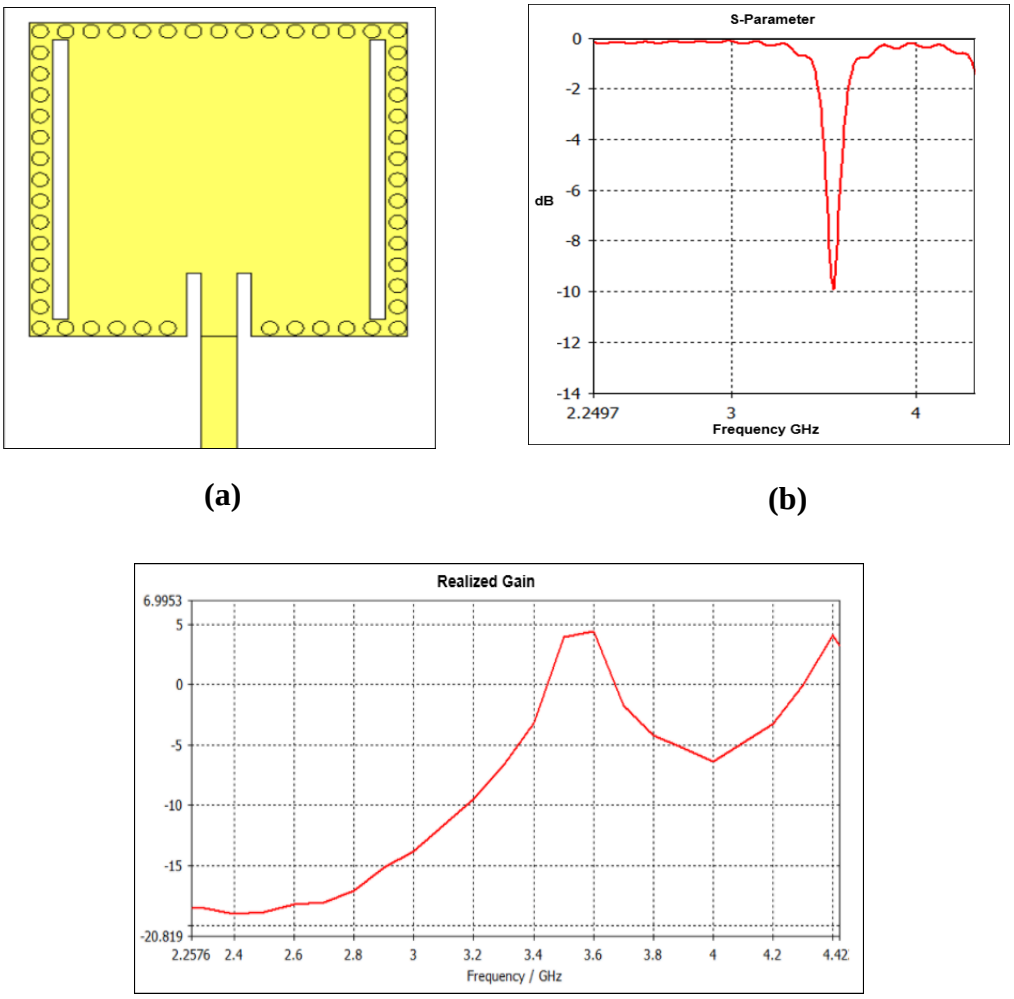


Figure 5. (a) Microstrip Feed with SIW Cavity and (b) Simulated S-Parameter (c) Realized Gain

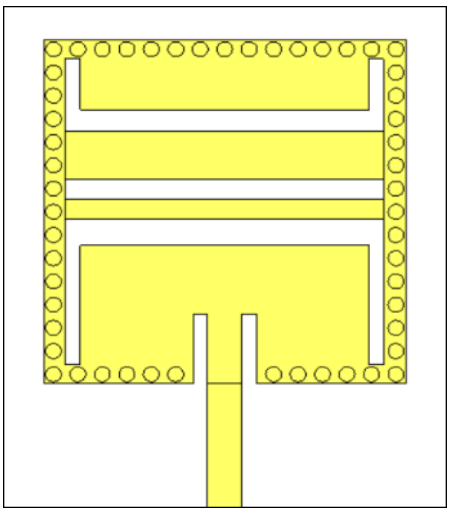
Fig. 5(a) Substrate Integrated Waveguide (SIW) cavity-based antenna with vertical slots is developed. This configuration aims to combine waveguide-like field confinement with slot-based resonance tuning. The antenna layout features a rectangular radiating surface

bordered by a series of metallized via holes, which mimic the sidewalls of a conventional metallic waveguide, effectively forming an SIW cavity. These vias guide the electromagnetic energy and limit leakage, enabling controlled propagation within the dielectric substrate. The cavity's both right and left side have two symmetrically engraved vertical slots. These slots serve two primary purposes, they alter the current distribution on the surface, inducing distinct resonance characteristics, and they enable coupling between different field modes, allowing the antenna to support higher-order or hybrid modes.

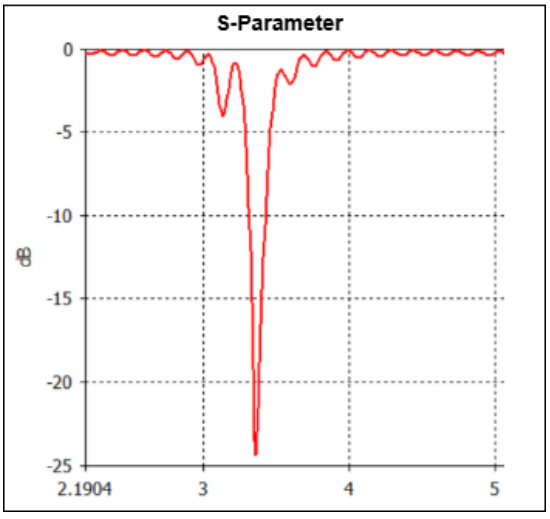
Fig. 5(b) shows that S-parameter (S11) response, it is observed that the antenna exhibits a resonance around 3.6 GHz, with a return loss below -10 dB, indicating effective impedance matching and radiation at that frequency. Realized Gain plot is demonstrated in Fig. 5(b). it shows that Antenna 1 exhibit one Radiational Null (RNs) at 4 GHz. The cavity and vertically slot's destructive interference is the cause of this null.

3.3.2 Antenna 2

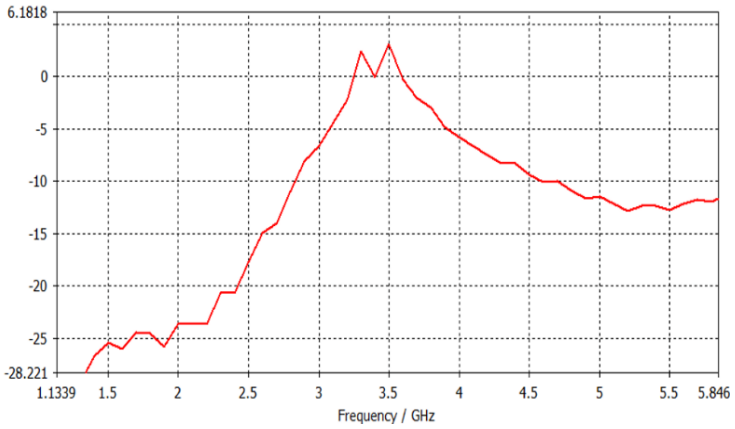
In the second stage, Antenna 2 evolves from Antenna 1 by introducing a parasitic half-mode patch resonator adjacent to the driven SIW patch. Two horizontal slots printed on patch this is achieved through the integration of a two inverted C-shaped distributed by the middle horizontal slot.



(a)



(b)



(c)

Figure 6. (a) Antenna 2, 2-inverted C-shaped separated by Horizontal slot, (b) Simulated S-Parameter, (c) Realized Gain

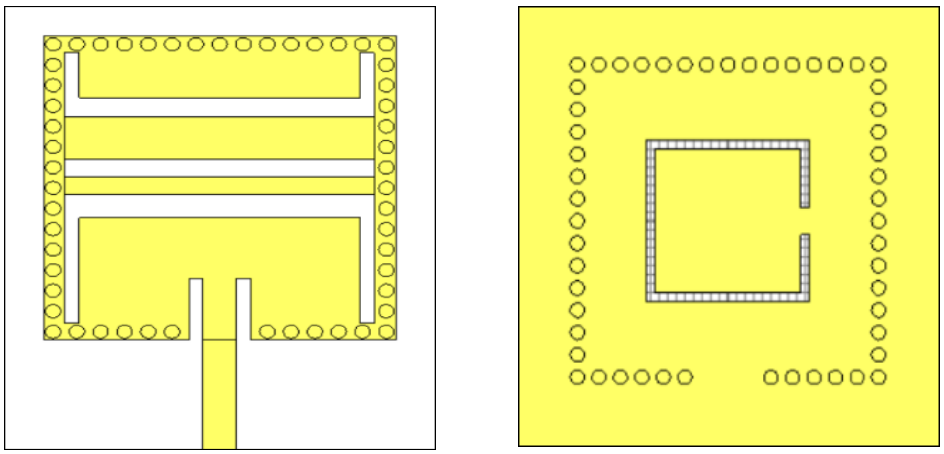
Fig. 6(a) The inclusion of inverted C-shaped slots introduces reactive loading, which perturbs the current distribution and supports the emergence of additional resonant modes. These slots operate as magnetic dipoles, coupling effectively to the cavity's field distribution. The horizontal slot, acting as a coupling aperture, enhances the interaction between the resonant fields of the C-slots.

Fig. 6(b) The S11 response distinctly exhibits a Dual-Resonance behavior where 1st is maximum reflection but 2nd resonance shows minimum reflection, with prominent return loss minima observed near 3.15 & 3.4 GHz. The two resonant modes are primarily induced by the inverted C-shaped slots, which introduce localized perturbations in the current distribution, effectively supporting dual-frequency operation. The narrow horizontal slot positioned between the C-slots enhances electromagnetic coupling across the upper and lower portions of the cavity, thereby enabling controlled energy transfer and precise tuning of the second resonant mode. The return loss at these frequency dips at −24 dB, which confirms effective power transfer and minimal reflection.

Antenna 2 displays 2-Radiational Nulls (RNs) at 1.9 GHz & 2.5 GHz, as seen in Fig. 6(c). These nulls occur due to out-of-phase surface currents canceling the far-field radiation, a behavior indicative of mode suppression outside the designed passbands.

3.3.3 Antenna 3

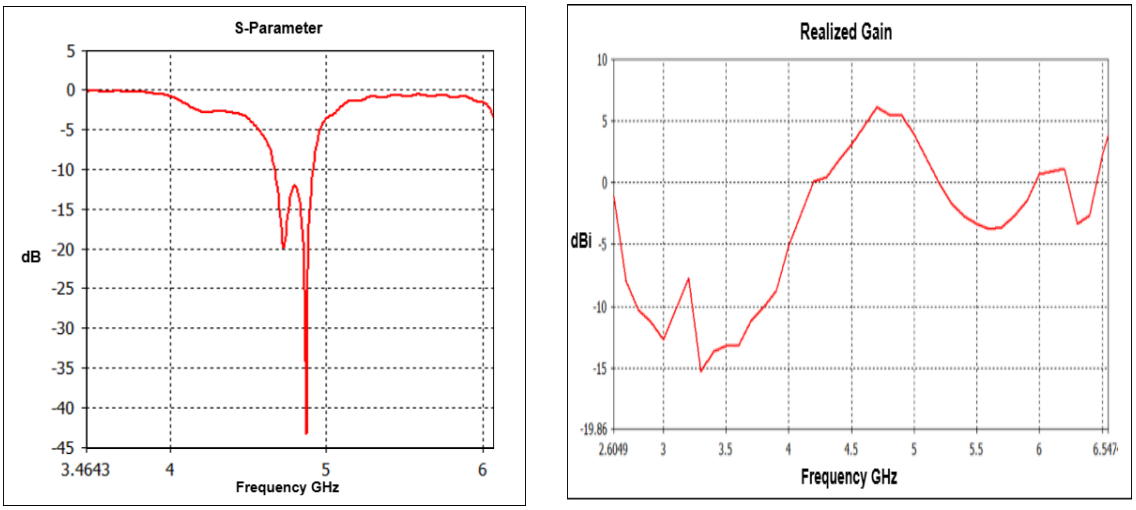
In the final stage, Antenna III builds upon the configuration of Antenna II by embedding a ring-shaped slot on the metallic ground plane. This additional ground modification significantly influences the surface current distribution and enhances the electromagnetic coupling between the resonant elements. The resulting structure effectively forms two gap-coupled half-mode SIW resonators, thereby realizing a dual resonance Antenna without filtering selectivity. Each stage of evolution contributes to the antenna's ability to perform both Antenna response and radiation within a compact footprint.



(a) (b)

Figure 7. (a) Antenna 2, 2-inverted C-shaped separated by Horizontal slot, (b) Ring Slot on Ground

Figure 7 shows that a key enhancement at this stage is the inclusion of a ring-shaped slot precisely etched into the ground plane beneath the SIW cavity. This ring slot plays a significant role in the overall electromagnetic behavior of the antenna by introducing a localized resonant mode. The slot interacts with the fields within the cavity, effectively shaping the current distribution and creating a two peaks resonance. The feeding mechanism consists of a centrally positioned microstrip line that excites the cavity in a symmetrical manner, promoting balanced field distribution and stable resonance. This combination of SIW technology and a ground-plane slot enables the integration of Dual Band radiation functionalities into a compact and planar structure.



(c) (d)

Figure 8. Dual Resonance Antenna (c) Simulated S-Parameter (d) Realized Gain

Figure 8. (c) The S11 plot shows a prominent two resonance dip at 4.78 and 4.9 GHz, with a return loss below -10 dB, indicating strong resonance and excellent impedance matching at that frequency. This means the structure allows maximum power transfer with minimal signal reflection. The sharpness and depth of the dip suggest that the design supports a highly selective resonant mode. Outside this frequency range, the return loss increases, implying reduced transmission efficiency. These characteristics demonstrate the structure's ability to operate effectively at a specific frequency while minimizing performance at others.

When compared S-Parameter to the earlier designs Antenna 1, Antenna 2 and antenna 3 structure exhibits significantly improved reflection characteristics. Antenna 1 shows a relatively shallow S11 response, with a return loss of around -10 dB, indicating that only about 90% of the input power is accepted, and the rest is reflected. Antenna 2 shows moderate improvement with a return loss nearing -24 dB and it can generate single resonance band. also still lacks sharp frequency selectivity. In contrast, the third design antenna 3 demonstrates two Resonance bands with a deep and narrow S11 notch near 4.78 and 4.9 GHz. This implies highly efficient power transfer and strong resonance at the target frequency. The steep slope on either side of the resonance point in the latest design indicates tighter frequency control and enhanced performance in rejecting nearby undesired frequencies, which was not as prominent in the earlier designs.

Figure 8. (d) The highest gain of 6.15 dBi is displayed in the realized gain graph associated with Antenna 3 design, showing effective radiation and low mismatched losses at the desired frequency. Notably, the gain curve exhibits two Radiation Nulls (RNs) around 3.3 GHz, and 6.3 GHz outside the passband, where the gain drops sharply to approximately 0 dBi or lower. These nulls correspond to frequencies where radiation is significantly suppressed, likely due to destructive interference or impedance mismatches, which may result from the resonant behavior introduced by the ring slot etched on the ground plane.

When compared with earlier stages of Antennas:

Antenna 1 presents a relatively flat and low gain profile, with peak gain exceeding 4.8 dBi. It has no strong frequency selectivity and shows one null away from the passband, indicating basic radiation behaviour without advanced field shaping.

With a gain peaking at about 3.5 dBi, **Antenna 2** exhibits a moderate improvement; nonetheless, the frequency transition is gradual and displays two nulls outside of the passband.

In contrast, **Antenna 3** design offers both higher gain and sharper frequency response. The presence of a radiation null followed by a strong gain peak demonstrates that the antenna structure is not only radiating efficiently but is also selectively enhancing radiation at the desired frequency while suppressing it elsewhere.

3.4 Working Mechanism

To better understand the work behavior of the proposed structure, this section examines its radiation characteristics, the origin of Radiation Nulls (RNs) and the surface current distributions on the radiating patch are illustrated at the corresponding resonant frequencies to provide insight into the electromagnetic behavior of the structure[19].

The suggested 2 C-inverted shaped slot-loaded structures' surface current distributions are examined at frequencies f1 and f2 in Figure 9. The results indicate that the surface currents flowing in opposite directions across the upper and lower slots effectively cancel each other as shown in Fig (a) and (b).

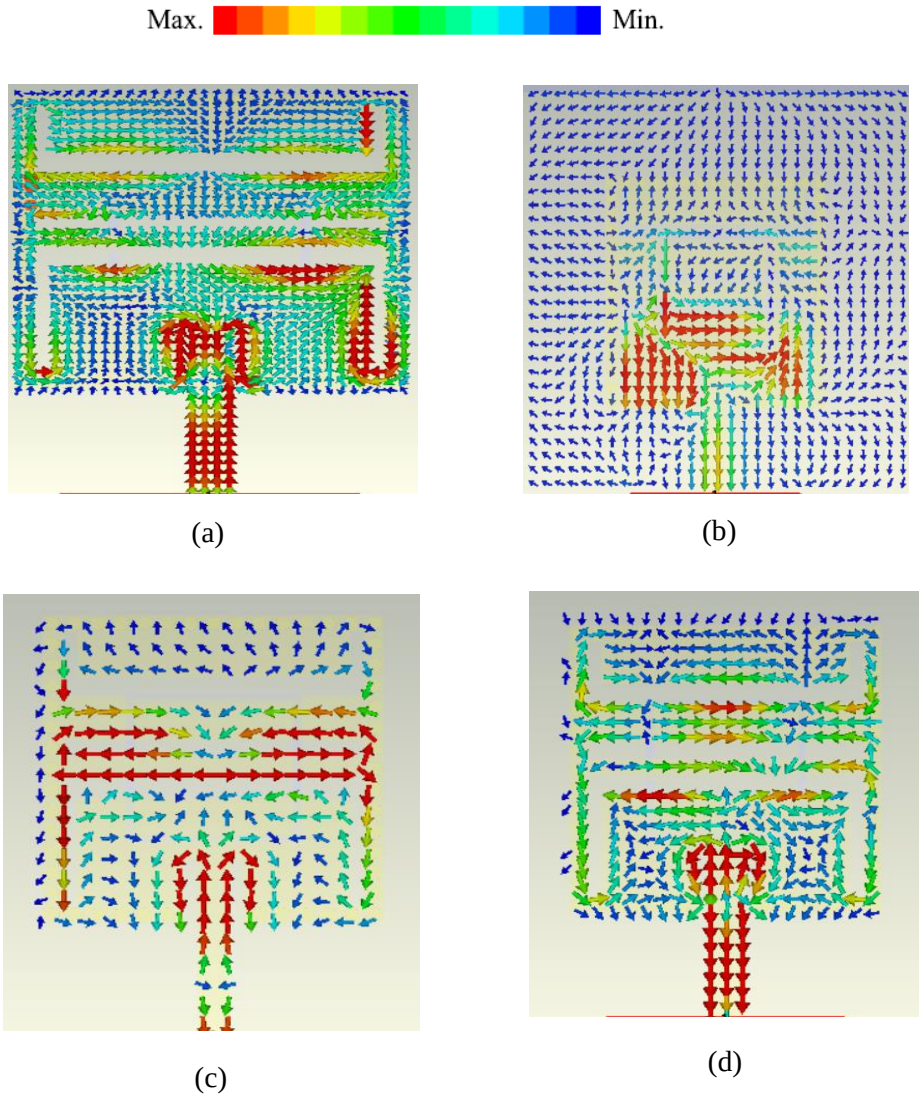


Figure 9. Distributions of Current on the Antenna Structure at (a) f_1 = 4.73 GHz (b) f_1 = 4.87 GHz (c) f_{n1} = 3.3 GHz (d) f_{n2} = 6.3 GHz

Figure 9(c) illustrates the surface current and electric field distributions of the antenna structure featuring a horizontal slot separated by the two C-inverted shaped slot etched on the patch and ring structure slot on the ground plane, evaluated at the frequency corresponding to the first observed null (fn1) near 3 GHz. The current distribution reveals that opposing surface currents are induced on the upper and lower arms of the slot, oriented perpendicularly to its length. These currents exhibit strong anti-symmetry, leading to mutual cancellation in the far-field due to destructive interference. Correspondingly, the electric field profile displays a pronounced phase reversal across the central axis of the slot, further suppressing radiation in the boresight direction.

This destructive field coupling significantly reduces the antenna's radiation efficiency at this frequency and results in a well-defined null in the realized gain pattern. Such behavior confirms that the slot acts as a resonant perturbation element, selectively disrupting radiation at specific frequencies. Notably, the location of this null (fn1) is highly sensitive to the slot geometry—particularly the insertion depth of the two C-inverted shaped arms. By modifying this parameter, the resonant interaction responsible for the radiation null can be effectively tuned, offering design flexibility in shaping the antenna's frequency response.

The microstrip feed line contributes minor radiation, which effectively forms a secondary coupling mechanism between the input source and the radiating structure. As illustrated in Fig. 9(b), the radiation emitted directly from the microstrip section and its inset coupling into the half-mode patch resonator exhibits an out-of-phase relationship with the main radiation from the patch itself. This phase opposition between the two radiating sources leads to partial cancellation in the far-field, particularly at the frequency identified as fn2 (6.3 GHz). The resulting destructive interference manifests as a radiation null in the antenna's gain response. This mechanism highlights the sensitivity of the antenna's behavior to feed-line geometry and coupling structure, offering a means of controlling frequency response through careful design of the excitation configuration but this antenna design shows poor frequency selectivity because of this null generated out of the band. Hence above simulated Antenna shows higher gain and Two Resonance frequencies without Filtering behavior. To overcome this problem and to increase the Frequency Selectivity 3rd order Filtenna is Proposed.

CHAPTER IV

PROPOSED THIRD ORDER FILTENNA DESIGN

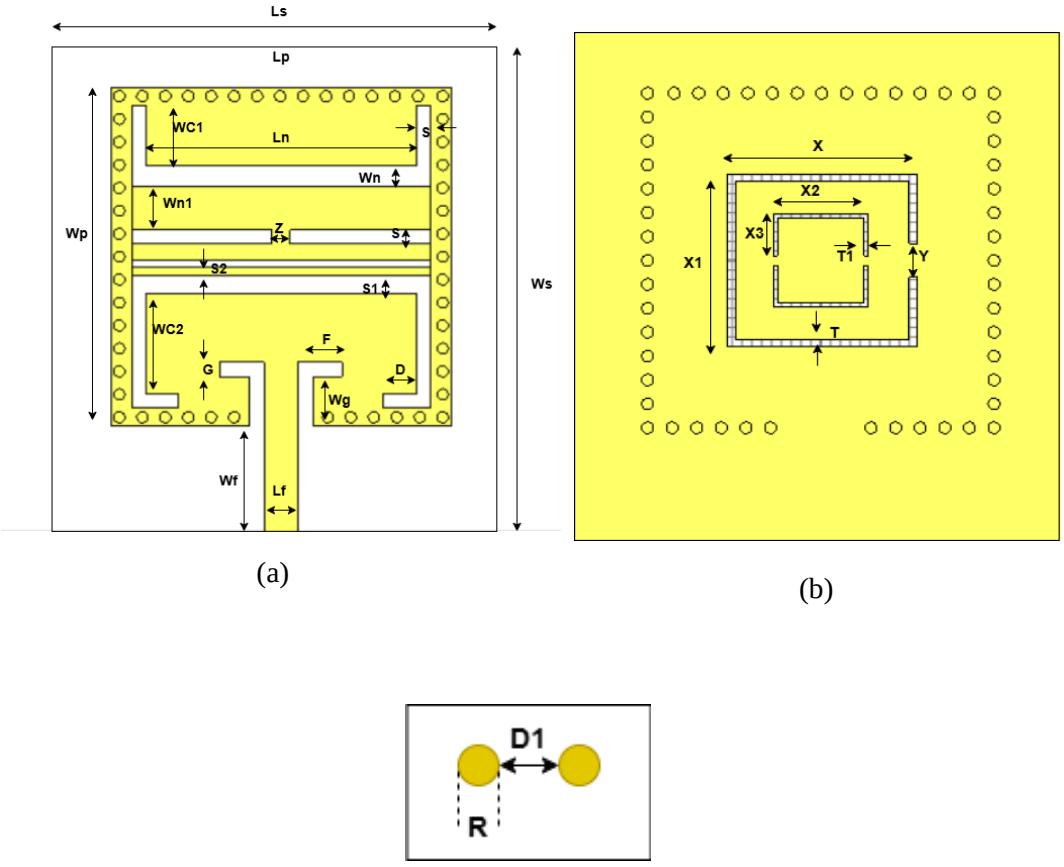
4.1 Introduction

The transition from a Second-Order Antenna to a Third-Order resonance configuration in Filtenna design offers several performance enhancements and greater functional flexibility. A Second-Order Antenna typically supports dual-band operation, also this Antenna has no intrinsic filtering characteristics fig[8]. While effective for simple wireless applications, its spectral control is limited[20]. In contrast, a Third-Order Filtenna design introduces with three resonance frequencies, which contributes to a more refined frequency response. The extra peak allows for the inclusion of a third operational band or the formation of a controlled notch between adjacent passbands[21]. Better selectivity and more intricate filtering properties are the outcomes of this. Moreover, the inclusion of a third resonance often leads to deeper Radiation Nulls between peaks, contributing to better interference mitigation and spectral efficiency.

4.2 Proposed Third Order Filtenna Design

The structural layout of the Proposed Third-Order Antenna-integrated Filtering system. The design is based on a rectangular substrate-integrated waveguide (SIW) cavity that incorporates a pair of symmetrically positioned two inverted C-shaped separated by the H-shaped on patch and ring structure slot that is carved in opposing orientations and printed on the ground plane. These slots serve as resonant perturbations that enhance frequency selectivity by introducing additional resonant modes. A coplanar waveguide (CPW) feed mechanism is implemented to efficiently excite the structure while maintaining planar integration and wideband impedance matching.

The entire configuration is realized on a single-layer Rogers RT/Duroid 5880 substrate with thickness of 1.5, which features a low dielectric constant of 2.2 and an ultra-low loss tangent of 0.001, contributing to minimal insertion loss and stable high-frequency performance. This third-order configuration supports three well-defined resonance peaks, offering enhanced spectral control and sharper filtering characteristics compared to conventional lower-order implementations.



(a) (b)

(c)

Figure 10. (a) Proposed Simulated Third Order Filtenna, (b) Ground Plane (c) Radius & Distance of SIW Cavity

4.3 Design Parameter

The Table 2. shows that the design parameters of the Third Order Filtering Antenna.

Lp	Wp	Ln	Wc1	Wn	Wn1	S	S1	S2	Wc2	Wg
37	37	29.5	6.5	2.3	4.8	1.5	2.2	0.6	11.1	5.6

Z	Lf	Wf	G	F	R	D1	Y	D	X	X1
2.4	3.7	11.5	1.4	4.2	0.8	0.9	19	4.2	19.3	18

X2	X3	T	T1	Ls	Ws
9.6	4.3	0.8	0.4	50	54

Table 2. Filtenna Design Parameters (In mm)

4.4 Filtena Design Process and Evolution

The design evolution leading to the development of the proposed Filtenna is outlined in Fig. 11. Starting from the configuration of Antenna 3, the structure was strategically modified to enhance its electromagnetic performance. Specifically, the revised design incorporates two inverted C-shaped elements that are symmetrically placed and separated by an H-shaped metallic structure located on the radiating patch. In addition to these changes on the patch side, a circular ring-shaped slot is etched onto the ground plane. These modifications collectively form Antenna 4, referred to as the proposed Filtenna, which is designed to deliver improved filtering and radiation characteristics.

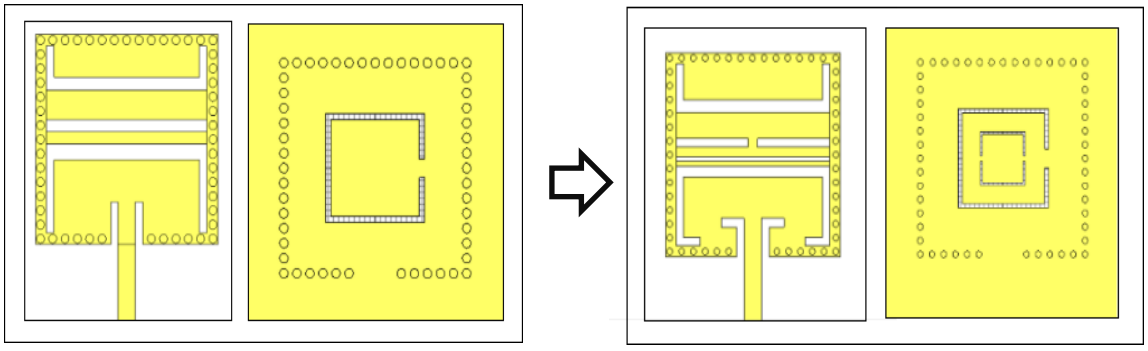


Figure 11. Proposed Filtenna Evolution

A comparative analysis between Antenna 3 and Antenna 4 is presented in Fig. 12, which illustrates their reflection coefficients, gain profiles, and input impedance behaviors. As shown in Fig. 12, Antenna 3 exhibits two resonance peaks within the operational frequency band, indicating its dual-band nature. In contrast, Antenna 4 demonstrates three distinct resonance points within the same frequency range.

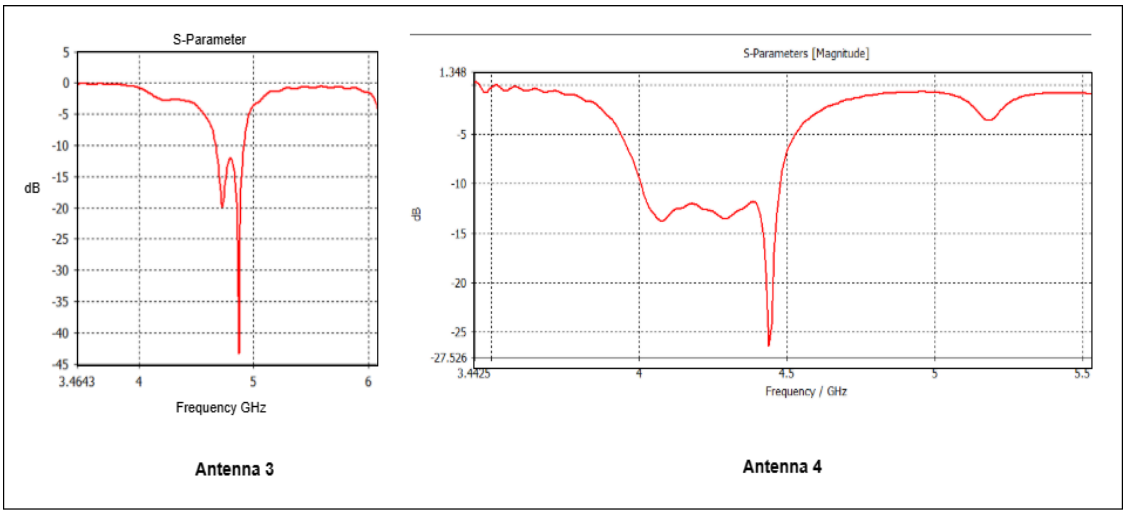


Figure 12. S-Parameter Comparison of Simulated Antenna Designs

This additional resonance in Antenna 4 results in a broader effective bandwidth, allowing it to support a wider span of frequencies within the desired passband. The enhanced bandwidth is advantageous for modern communication systems that demand high data throughput and reliable signal transmission across multiple channels.

Moreover, the frequency selectivity of each design is evaluated based on the presence of Radiation Nulls (RNs), as depicted in Fig. 13. Antenna 3 generates two Radiation Nulls within its operating spectrum, whereas Antenna 4 introduces a third null. The emergence of this additional RN in Antenna 4 plays a crucial role in suppressing unwanted frequency components outside the desired band.

This improvement in selectivity enables the proposed Filtenna to act as an effective bandpass filter, significantly attenuating out-of-band signals and enhancing overall system performance. The number of resonant peaks and RNs also provides insight into the filter order of the antenna structure, suggesting that Antenna 4 achieves a higher-

order response compared to its predecessor.

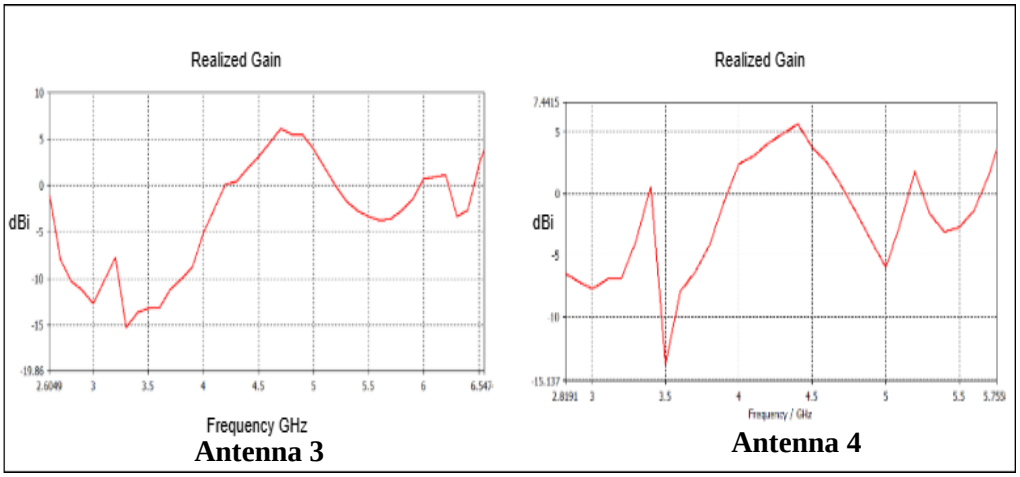


Figure 13. Realized Gain Comparison of Simulated Antenna Designs

The structural transformation from Antenna 3 to Antenna 4—through the integration of tailored patch and ground plane features—not only enhances the bandwidth and selectivity but also demonstrates a systematic approach to embedded filtering within antenna systems. These enhancements make Antenna 4 particularly suitable for applications in wireless communication systems that require compactness, frequency control, and efficient spectrum utilization. By combining radiation and filtering functions into a single integrated component.

4.5 Working Mechanism

To further elucidate the operating mechanism of the proposed two inverted C-shaped separated by the H-shaped on patch and ring structure slot printed on ground plane third-order Filtenna[22], this section delves into its radiation behavior and the formation of three Radiation Nulls (RNs). A comprehensive investigation is carried out to understand the underlying radiation principles, particularly by analyzing the structure referred to as Antenna 4.

Antenna 4 can be structurally interpreted as an integration of two subsystems, the previously developed Antenna 3 and an additional ring structure slot printed on ground plane filtering unit. Antenna 3 inherently supports two Radiation Nulls due to its

embedded resonant elements, while the incorporation of the H-shaped and ring structure introduces an extra radiation null. This configuration culminates in three distinct Radiation Nulls, thereby improving out-of-band suppression and overall selectivity.

To gain physical insight into the radiation mechanism and validate the presence of the nulls, the surface current and electric field distributions at the three resonant frequencies are illustrated in Figs. 14 and 15. These resonances are associated with the fundamental resonant mode of a half-wavelength resonator and two half-mode patch resonators, each contributing to the overall frequency response.

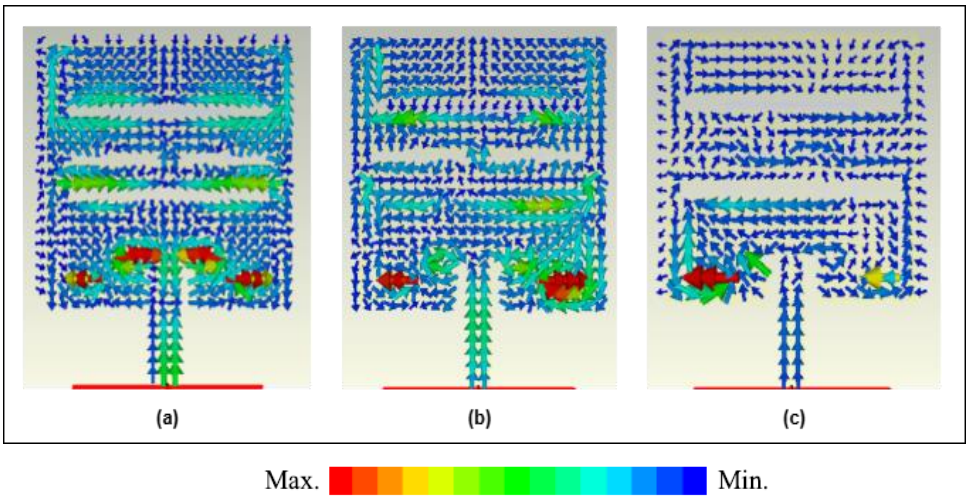


Figure 14. Surface Current Distribution at (a) f 1 = 4.08 GHz, (b) f 2 = 4.29 GHz and (c) f 3 = 4.438 GHz

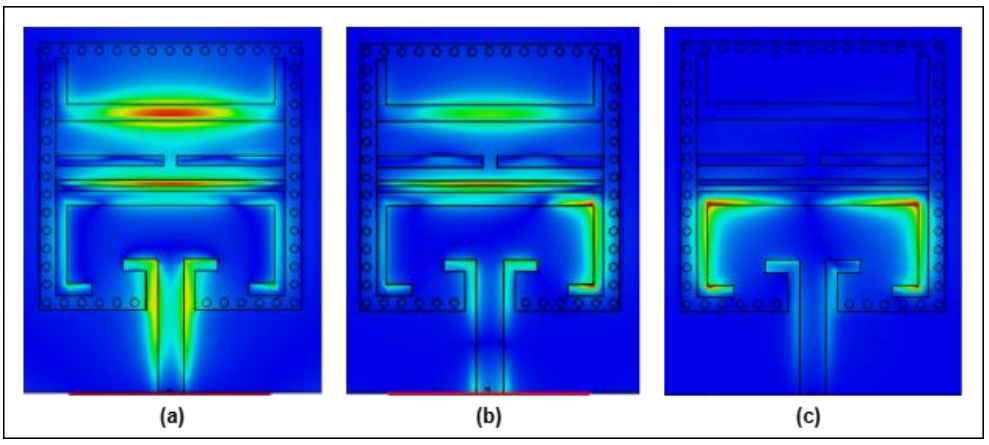


Figure 15. Distribution of the Electric Field at (a) f 1 = 4.08 GHz, (b) f 2 = 4.29 GHz, and (c) f 3 = 4.438 GHz

The surface current distribution at three different frequencies (4.08 GHz, 4.29 GHz, and 4.438 GHz) illustrates in figure 14. the resonant behavior and operating characteristics of the proposed filtering antenna. At 4.08 GHz, the surface current is relatively weak and confined mostly to the feedline and lower part of the structure, with minimal excitation of the upper resonating elements as shown in fig 14(a). This indicates a stopband response, where the antenna does not support efficient radiation. In figure 14(b) as the frequency increases to 4.29 GHz, the surface current becomes more pronounced and symmetrically distributed across the radiating cavity and ring slot regions. Clear current loops form, signifying strong resonance and efficient energy transfer from the feedline to the radiating elements, suggesting that the antenna is operating in a passband mode. At 4.438 GHz, the surface current density reaches its peak, especially around the slot edges and lower cavity, demonstrating high field intensity and strong directional current flow shown in fig 14 (c). This pattern confirms a resonant state with maximum radiation efficiency, indicating that the antenna is fully excited and effectively radiating energy at this frequency. The progression of current distribution across these frequencies validates the filtering functionality and selective radiation behavior of the design.

Figure 15**.** The electric field distributions at 4.08 GHz, 4.29 GHz, and 4.438 GHz reveal the resonant characteristics of the proposed Filtenna. At 4.08 GHz, the field is concentrated near the feed region with limited spread, indicating weak radiation and operation near a stopband illustrate in figure 15 (a). As the frequency increases to 4.29 GHz, the E-field becomes more uniformly distributed across the cavity and slot areas, signifying stronger resonance and effective radiation illustrate in figure 15 (b). At 4.438 GHz, the field intensity peaks and forms clear standing wave patterns near the slots, confirming excitation of a higher-order mode with maximum radiated energy shown in figure 15 (c). These field profiles support the intended bandpass filtering and radiation behavior of the antenna.

Filtenna exhibits characteristics of a TM11 mode at the 1^{st} resonance. the surface current is strongly concentrated in two symmetrical arms with a clear current loop and phase reversal, indicating standing wave behavior. The electric field is predominantly vertical and symmetric across the patch, with field maxima near the slot edges, resembling a half-wavelength resonance. Meanwhile, the magnetic field circulates

around the current paths, strongest near the slots, which is consistent with transverse magnetic mode behavior. The resonance likely arises from a half-mode patch loaded cavity, where structural modifications shift the resonant behavior to higher-order TM configurations. In rectangle patch antennas, transverse magnetic modes are referred to by the TM11 mode designation, where:

$$f_{mn} = \frac{c}{2}\sqrt{\left(\frac{m}{L}\right)^2 + \left(\frac{n}{W}\right)^2}\frac{1}{\sqrt{\varepsilon_r}} \qquad (8)$$

Where:

- m, n = mode numbers
- L and W = patch dimensions
- ε_r = the substrate's dielectric constant

The observed field patterns reveal that the primary radiation originates from the two half-mode patch resonators, while the half-wavelength resonator contributes more to the filtering behavior than to radiation itself. The Radiation Nulls emerge due to destructive interference between modes or cancellation at specific spatial positions due to opposite phase currents. The resonance condition for the half-wavelength resonator, which is a critical component in forming the transmission profile, can be modeled by:

$$f_r = \frac{c}{2L\sqrt{\varepsilon_{\text{eff}}}} \qquad (9)$$

Where:

- L is the resonator's physical length;
- εeff is the substrate's effective dielectric constant.
- c is the speed of light
- L is the physical length of the resonator

This relationship confirms that the resonant frequency is mainly determined by the physical length L of the resonator and the dielectric environment. Since the structure of the half-wavelength resonator is isolated from strong radiating sections, its impact on the radiation pattern is limited, but its role in filter shaping is significant.

The antenna exhibits characteristics of a split TE_{110} mode at 2nd Resonance, commonly found in half-mode SIW cavity structures. The surface current pattern shows symmetrical distribution with strong activity around the slots, indicating effective magnetic interaction. TE-mode excitation is confirmed by the electric field's primary concentration close to the slots & radiating regions. The creation of circular loops in the magnetic field around the coupling zones lends additional support to this mode. These combined field behaviors indicate that the antenna achieves dual-mode resonance, allowing for both efficient radiation and filtering performance. The resonant frequency for such a mode is governed by the standard rectangular cavity formula:

$$f_{mn} = \frac{c}{2} \cdot \sqrt{\left(\frac{m}{a_{\text{eff}}}\right)^2 + \left(\frac{n}{b_{\text{eff}}}\right)^2} \cdot \frac{1}{\sqrt{\varepsilon_r}} \qquad (9)$$

Where:

- f_{mn}: Resonant frequency for the TE_{mn} mode (Hz)
- c: Speed of light in vacuum ($\approx 3 \times 10^8$ m/s)
- ε_r : Relative permittivity of the substrate
- a_{eff}: Effective width of the cavity
- b_{eff}: Effective height (or length)
- m,n: Mode indices (for TE_{110}, m = 1, n = 1)

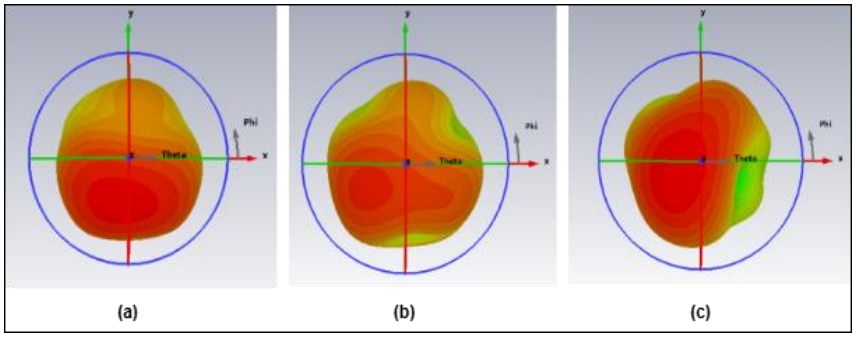


Figure 16. 1D View of Radiation Patterns at (a) 4.08, (b) 4.29, and (c) 4.438 GHz.

The normalized radiation patterns at the resonant frequencies of 4.08 GHz, 4.29 GHz, and 4.438 GHz—corresponding to the lower and upper passbands—are illustrated in Fig. 16 for both simulation and measurement. The radiation characteristics are predominantly broadside, with minor angular deviations observed in some patterns due to perturbations in the cavity modes. The antenna exhibits acceptable polarization performance, with measured cross-polarization levels consistently below –14.6 dB. Furthermore, the simulated and experimental results align closely across the entire operating frequency range, confirming the accuracy of the design and modeling approach.

CHAPTER V

RESULT AND CONCLUSION

5.1 Results

The designed filtering antenna was simulated based on optimized physical parameters corresponding to normalized dimensions of approximately $0.78\lambda_g \times 0.78\lambda_g \times 0.0316\lambda^g$ is the guided wavelength calculated at the Center frequency of 4.26 GHz. Fig. 5(a) illustrates the simulated return loss characteristics. The reflection coefficient (|S11|) indicates that the antenna achieves an impedance bandwidth of 8.45%, covering the frequency range from 4.08 GHz to 4.44 GHz, where the return loss remains below –10 dB. Within this range, three resonant frequencies are clearly observable.

Two of these resonant modes originate from the combined structure of two inverted C-shaped stubs on the patch and a circular slot patterned on the ground plane. The third resonance is produced by an H-shaped slot intersected by a horizontal slot on the radiating patch surface. This configuration enables the antenna to exhibit distinct resonant behavior suited for filtering applications.

Fig. 13 presents the simulated gain response over the operational band. In the passband, the realized gain stays at an average of about 5.5 dBi. Importantly, three pronounced Radiation Nulls are observed at 3.6 GHz, 5.2 GHz, and 5.5 GHz. These nulls arise due to engineered electromagnetic coupling paths and contribute significantly to the antenna's out-of-band suppression characteristics. Furthermore, the coupling mechanisms responsible for the nulls can be independently controlled, allowing for flexible design adjustments as highlighted.

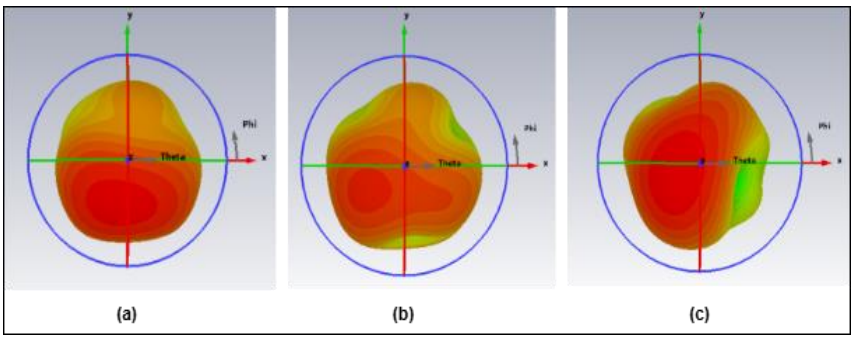


Figure 17. 3D View of Radiation Patterns at (a) 4.08, (b) 4.29, and (c) 4.438 GHz.

Figure 17 displays the simulated patterns of radiation at the determined null frequencies,

confirm that the antenna maintains stable radiation characteristics across the entire band of operation.

Table 3: Proposed Filtenna Compare with other existing Filtenna

Ref	BW%	Size (λ_g)	Gain (dBi)	Center Frequency (GHz)	RN
[10]	2.6	$0.017\ \lambda g^3$	4.3	5.5	2
[15]	6	$3.27\ \lambda_g{}^2$	6.45	5.02	2
[22]	8.33	$0.25\ \lambda_g \times 0.3\ \lambda_g$	2.3	2.4	2
[23]	15.2	$0.062\lambda g$	5.2	2.3	2
This work	8.45	$0.78\lambda_g \times 0.78\lambda_g \times 0.0316\lambda_g$	5.5	4.26	3

Table 3 presents a comparative study between the proposed filtering antenna and several representative designs reported in the literature. The comparison highlights the key advantages of the presented third-order filtering antenna. For a fair assessment, the table includes out-of-band suppression levels in the vicinity of the passband, which are critical indicators of filtering performance.

When compared to low-profile Filtennas such as the one reported in [10], the proposed design offers a significantly broader impedance bandwidth and enhanced gain, while maintaining a compact footprint and achieving superior suppression characteristics. In contrast to the wideband antenna described in [15], the proposed antenna demonstrates a more compact form factor, coupled with improved gain and more pronounced out-of-band attenuation. Furthermore, compared with the antennas detailed in [22] and [23], which aim to achieve low profile and wideband operation, the proposed design outperforms them in terms of bandwidth, gain, and suppression level, thus emphasizing its efficiency and effectiveness for integrated filtering applications.

5.2 Conclusion

This work presents a third order filtering antenna (Filtenna) is proposed, offering wide impedance bandwidth and effective out-of-band suppression. The antenna structure incorporates two inverted C-shaped elements, separated by an H-shaped slot on the patch, in conjunction with a ring-shaped slot etched on the ground plane. This configuration enables the excitation of three distinct resonant modes within the operational frequency band. Additionally, two Radiation Nulls are observed at the lower and upper frequency edges, which contribute to enhanced suppression of out-of-band signals. The overall design achieves a compact profile of $0.78\lambda_o \times 0.78\lambda_o \times 0.0316\lambda_o$, with a stable realized gain of around 5.5 dBi across a measured bandwidth of 8.45% (4.08–4.44 GHz).

CHAPTER VI

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